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SELF COMPENSATING CAPACITIVE FLUID LEVEL SENSOR

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Abstract. *This work describes the development of a capacitive level meter, with minimum size, and immune to interference of structures or features internal to the tank. The intended electrode set is a planar arrangement, insulated from the fluid, to be adhered to a fuelling nozzle or tank wall. The first intended use is a fast refuelling operation, on unknown fluid tanks, that may not be modified to allow for the measurement. The convenient electrode arrangement, accuracy and simplicity suggest potential for a wide range of applications.*

Keywords: *level meter, sensor, capacitive sensor*

1. INTRODUCTION

The problem faced was the need of a level sensor for a fast refuelling operation, with many possibilities for environment inside the fuel tank being refuelled, that were unknown, in the normal case. The available fuelling pressure is limited by regulations applicable to the intended use of the system, while the fuel flow is desired to be maximum, to minimize the fuelling operation time, requiring the maximum access area for the nozzle and tank vapor exhaust.

These requirements are immediately derived to: minimum access area required by the sensor, and structures internal to the tank could interfere with a capacitive sensor, therefore, the arrangement should be impervious to interference from anything but the fuel itself.

Level sensing is an old problem, with mature and reliable solutions, with many well known working principles. Were evaluated sensors based on floaters, capacitive, fluid pressure and echo.

Work exist in many technologies. Of the applications found, the solutions either could not accommodate for unknown conditions inside the fuel tank, or use access area, needed to maximize fuel flow.

The final arrangement was a capacitive sensor, with a planar set of electrodes, with features to compensate for undesired interference.

2. AVAILABLE TECHNOLOGY

Floater based sensors are reliable and precise, capable of exerting considerable force, suitable to actuate potentiometers, switches even valves. A common arrangement is to equip the floater with a magnet, that can close a magnetic switch when the desired level is reached.

Although proved, reliable and precise, this type of sensor requires, either, changes in the interior of the tank, incompatible with the application in hand, or a sensor to be inserted with the nozzle, that would take tank access area, needed for maximum fluid flow.

Capacitive sensors sense by measuring the capacitance variation due the change in the dielectric characteristic between electrodes, consequence of the varying fuel level. Typically, the electrodes are disposed parallel, facing one another, to maximize the potential capacitance, as can be seen in figure 1. The measurement is done by exciting one electrode with ac signal of suitable frequency, the level is indicated by the perceived impedance between electrodes. Many arrangements exist, examples can be found on (Reverter *et al.*, 2007), that requires particular conditions on the tank. Other approach is in (Bera *et al.*, 2006), that defines a bulky cylindrical sensor. Other solution is in (Bera *et al.*, 2014), with potential large electrodes, and uncertain immunity to the tank structure interference.

These sensors either require changes inside the tank, or will require access area, sacrificing flow, therefore operation time.

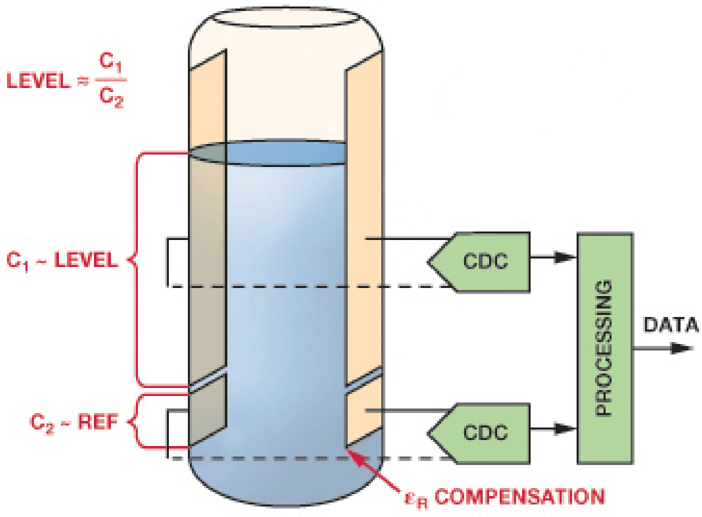

Figure 1. Example of capacitance based level sensor, (Wang, 2015)

Pressure sensors measure by converting the measured pressure caused by the fluid column. See figure 2. This type of sensor required precise knowledge of the fluid, and tank geometry.

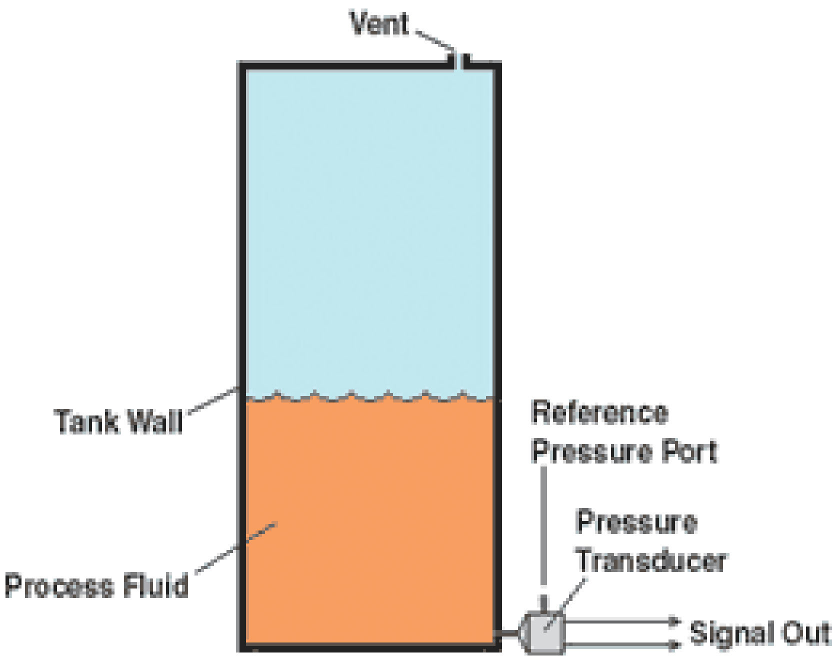

Figure 2. Example of level sensor by pressure, Hambrice and Hopper (2016)

Fluid level sensors by echo operate by measuring the distance between the sensor, usually installed at the highest point of the tank, and the fluid surface by a time to reflection of a burst of ultrasound or infrared light, figure 3.

This type of sensor has convenient aspects, like not touching the fluid, not particularly beneficial to our application. Requires change to the tank, or takes access area.

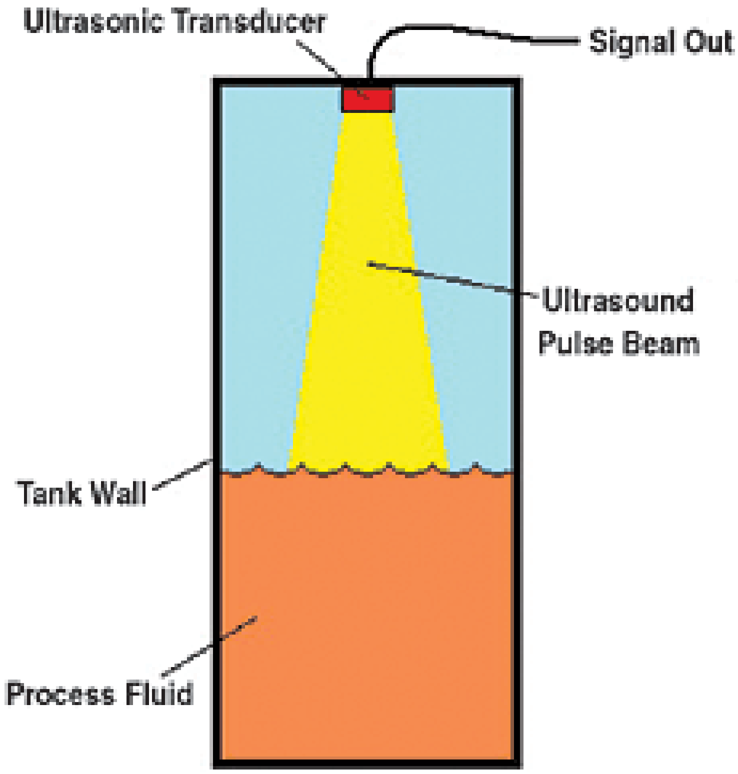

Figure 3. Example of level sensor by echo, Hambrice and Hopper (2016)

3. SELECTED SOLUTION

The selected working principle was seen on Baxter (1997), page 143, seen in figure 4. In the case, the electrode marked D is driven by an AC excitation, the signal sensed by the electrode marked S feeds back, shifting the phase by 180°, in the electrode marked F. For a low level, the amplitude required to minimize the signal received in the electrode S is low. When the level is high, the required signal on the electrode F to minimize the signal level sensed on the electrode S is high. The amplitude on electrode F is the output.

The arrangement proposed in Baxter (1997) may not be practical. If the input from the S electrode is not filtered, the system is susceptible to interference. If the S electrode input is filtered, the inevitable phase delay caused by the filter will affect the accuracy.

The proposed arrangement, pictured in 5, follows the same principle seen in Baxter (1997), but implemented in a more practical way. We propose generating the excitation signal, that is immediately inverted, for the compensation signal, assuring a precise phase shift. The compensation signal has its amplitude modulated, by means of a digital potentiometer. The sense electrode input passes through a filter and level detector.

The sensor is controlled by a microprocessor, that reads the filtered sense electrode, and modulates the compensation signal, controlling the digital potentiometer, minimizing the sense electrode signal modulus. The microprocessor calibrates the measurement and outputs the results, by serial interface. the arrangement is suitable for many types of output.

The sensor is a set of three electrodes in a planar arrangement, being excitation and compensation identical triangles inverted, the excitation electrode is narrow on the lower part, opposite of the compensation electrode, as seen on figure 6. For a low level of fluid on the electrodes, the excitation electrode exposed to the fluid will have a small area, due to the pointy end, limiting the effect on the sense electrode. For the same fluid level, the compensation electrode area exposed to the fluid is, much larger than the area of the excitation electrode, with a much larger effect on the sense electrode, for the same signal amplitude. For both electrodes to have a compensating effect on the sense electrode, the compensation electrode shall be driven with a much lower amplitude than the excitation electrode. For higher fluid levels, the amplitude on the compensation electrode should be higher, to minimize the reading on the sense electrode. The amplitude on the compensation electrode, after calibration, indicates the level measured.

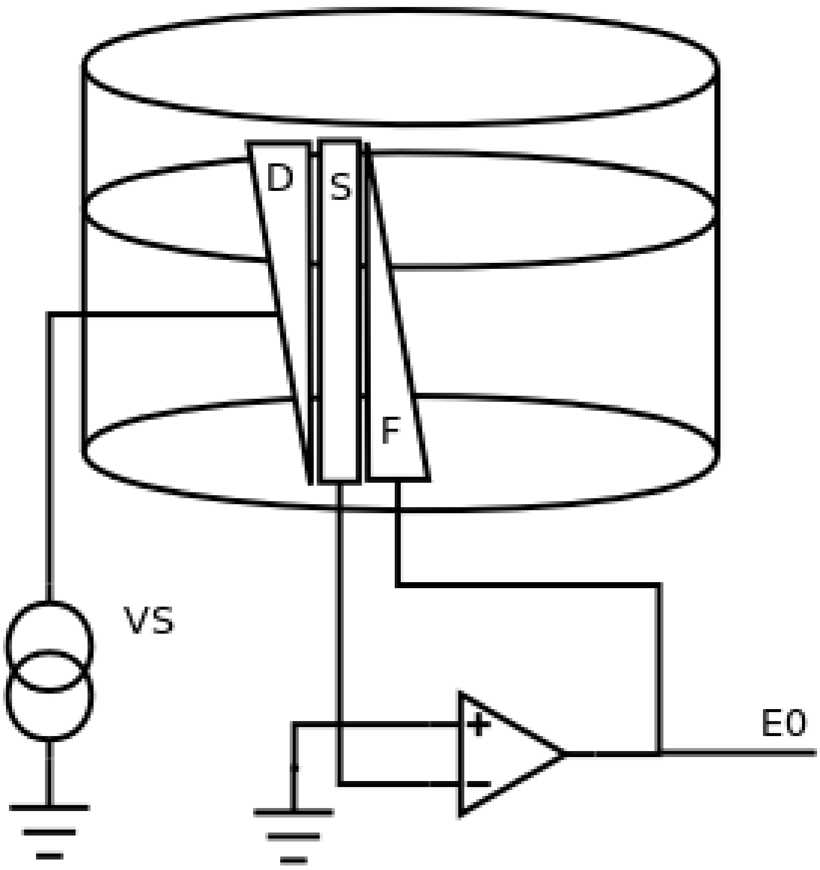

Figure 4. Electrode arrangement (Baxter (1997))

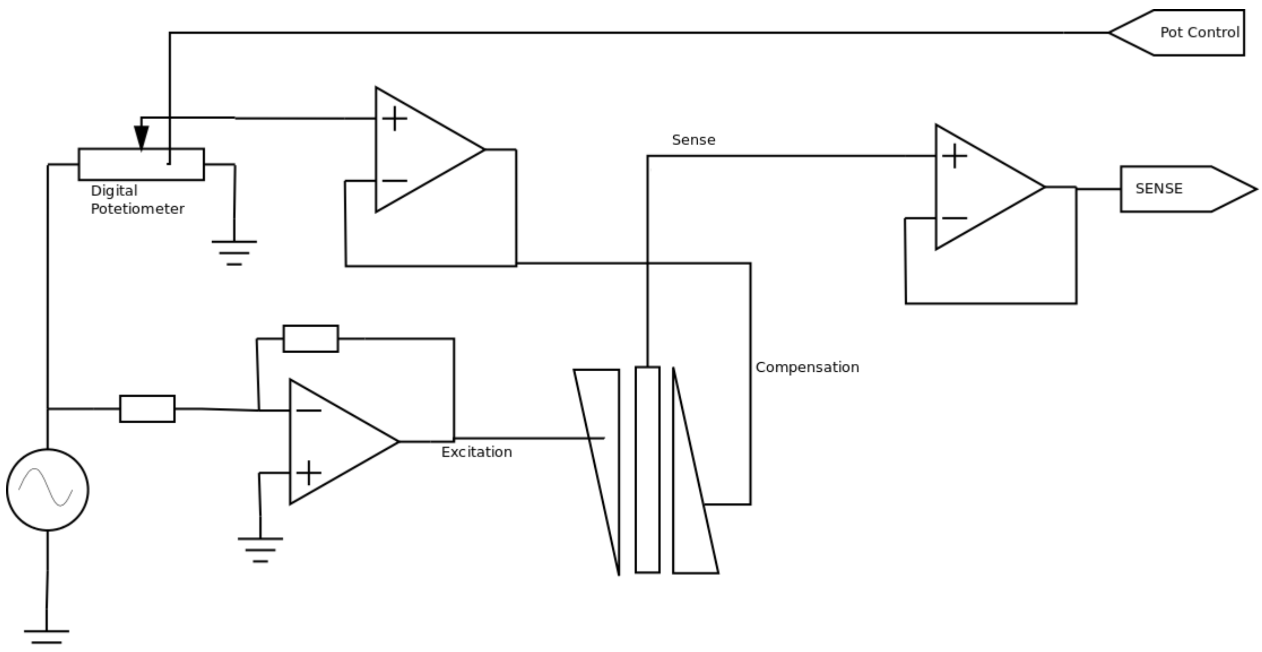

Figure 5. Scheme Proposed

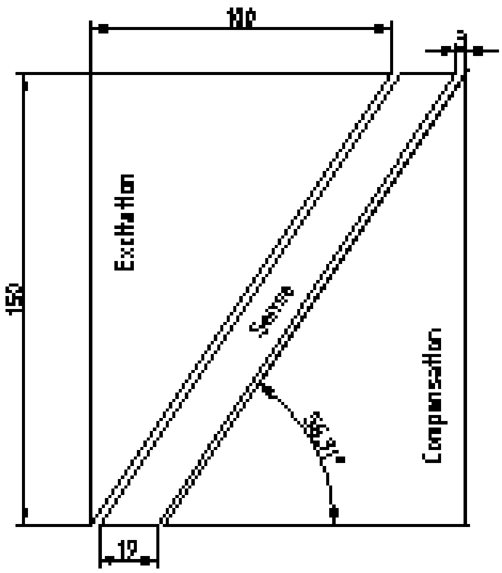

Figure 6. Electrode Arrangement

4. IMPLEMENTATION

The system components are: electrode, oscillator, filter and microprocessor.

In the implementation of all circuits, the LM324 was substituted by the TL084, with the proper arrangements on the power supply. The TL084 higher slew rate offered better results in the work frequency used.

To size the system parts, the electrode capacitances were estimated, first with the method in (Armijo *et al.*, 1990), then similar electrodes were cut from copper foil, and this capacitance measured with a RLC bridge.

The electrode was made of the material used in flexible printed circuits. The subtract is a $50\mu m$ thick poliimida film, coated with a thin coper film, that was chemically etched, as would with a printed circuit. The arrangement allows for a precise layout, and the poliimida resists well against heat and chemical attacks. The final electrode is a thin film, sturdy and well insulated from the fluid.

The capacitance between excitation and sense electrodes was measured and found to be around a few pF. The excitation frequency was chosen around 120KHz, suitable for capacitances of the required magnitude.

The frequency of 120KHz was the design frequency for the oscillator and filter.

5. ELECTRONIC CIRCUITS

The oscillator was designed for low distortion, a delay line feedback, with the frequency in 120KHz. The design was simulated in SPICE, figure 7, the result is in figure 8. The compensation signal amplitude modulation was implemented using the MCP41010 digital potentiometer, Microchip (2003).

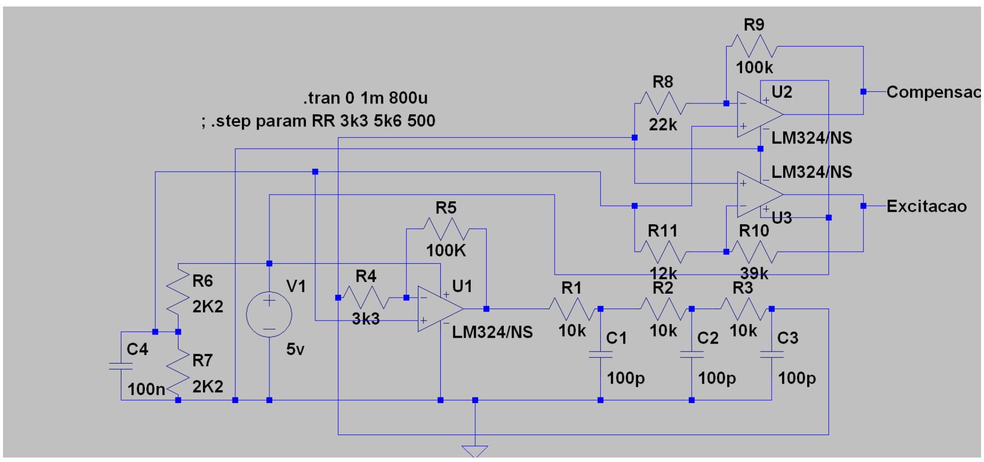

Figure 7. Oscillator Schematic

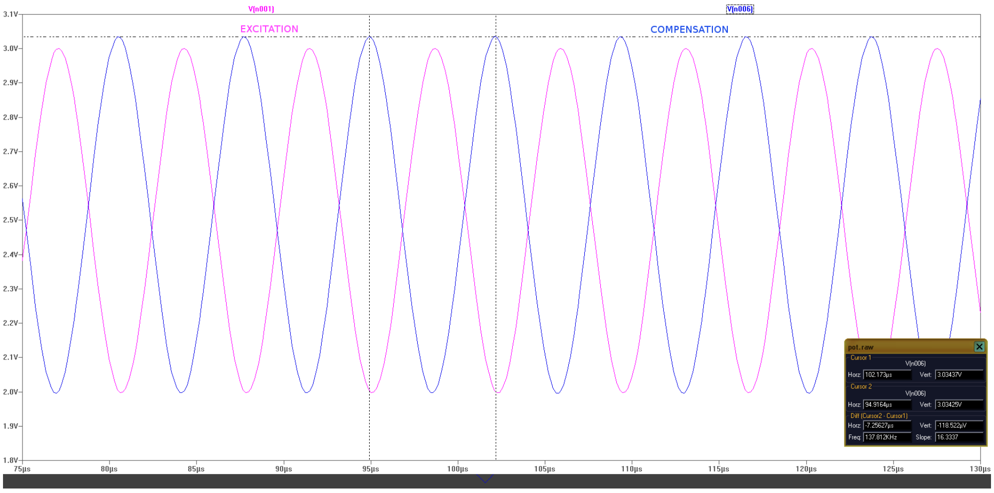

Figure 8. Oscillator Simulation Results (at points Comp and Exc

The filter designed to have two poles, based on (Texas, 2001), simulated in SPICE, figure 9, and the result presented in figure 10.

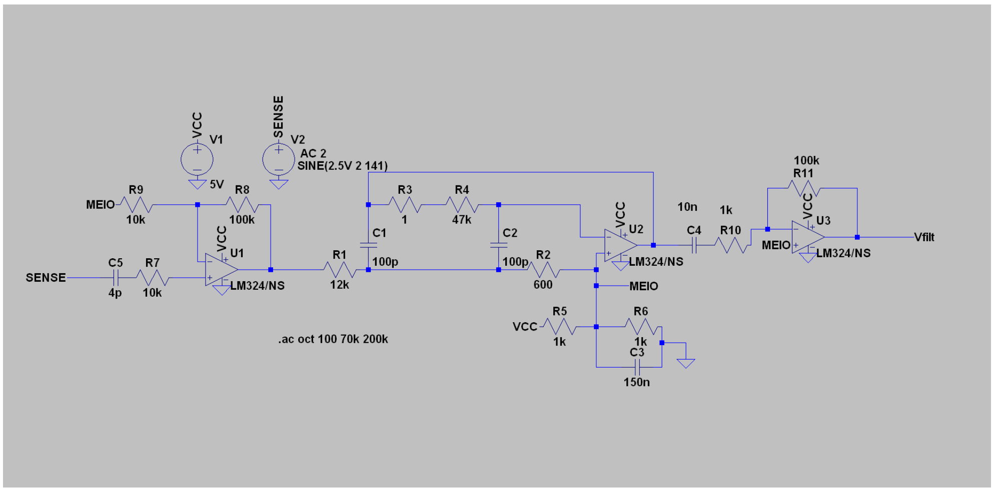

Figure 9. Filter Schematic

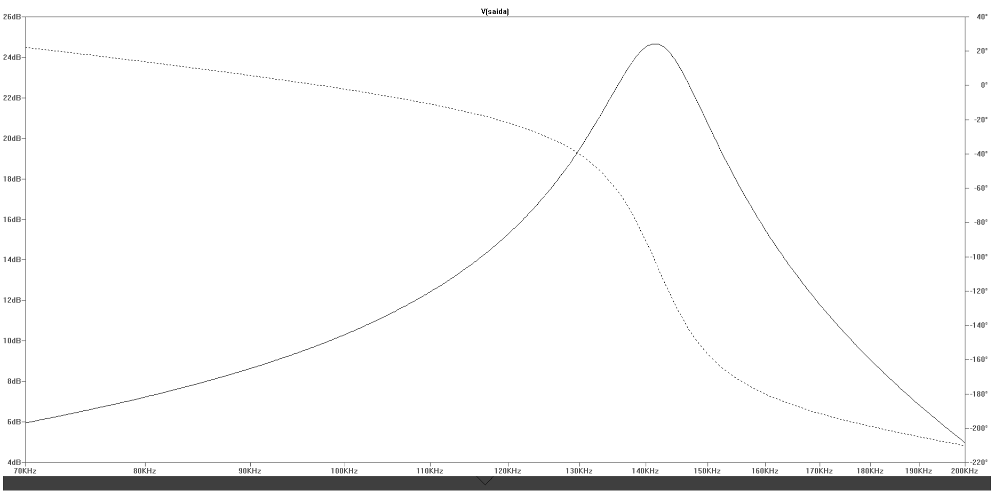

Figure 10. Filter Simulation Results at the points labelled Vfilt x SENSE

The peak detector is a precision rectifier using an operational amplifier and a NPN transistor, figure 11, and the simulation result in figure 12.

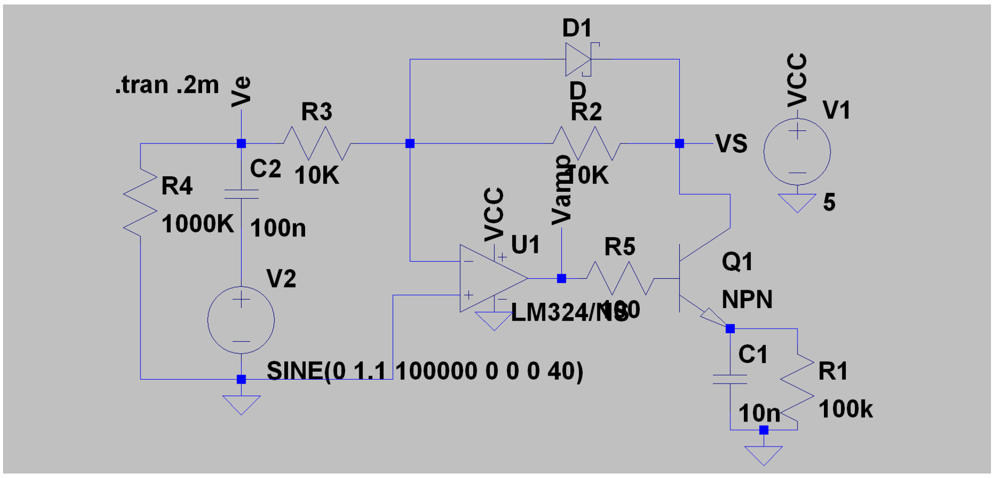

Figure 11. Peak Detector Schematic

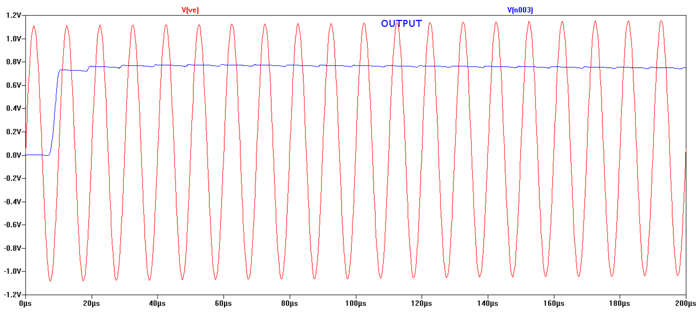

Figure 12. Peak Detector Schematic Simulation Results

The microprocessor selected was an Arduino Nano, for the ease of the development, and adequate processing power.

5.1 CONTROL

The microprocessor program is an iterative optimizer, controlling the digital potentiometer wiper to minimize the modulus of the amplitude in the sense electrode, read by the output of the peak detector. The system searches for the minimum output controlling the wiper position (C) of the digital potentiometer, monitoring the peak detector output (M). It can be said that $M = f(C)$, $f(C)$ representing the complete system. The point C_i is moved to $C_{i+1} = C_i + \delta C$, that will lead the reading M_i to $M_{i+1} = M_i + \delta M$. the next value for C will be $C_{i+2} = C_{i+1} + \frac{\delta M}{\delta C} * K$, being K a empirically determined constant for suitable performance, $K = 1$, in our case. The arrangement works naturally until the minimum M is reached, to assure the current value of C continually yields the minimum output M, the increment in the wiper position δC is forced to be different from zero.

When the electrode is completely immerse in the fluid, will require full amplitude on the compensation electrode. This condition also happens when the electrodes are completely in air. For this condition, we read the sense electrode with the compensation signal fully attenuated. The reading indicates which case is the case, depending of the value read, high when completely immerse, low when completely exposed.

6. RESULTS

The circuit was implemented as described, the electrode gradually immersed in water, in several points was found the wiper setting that minimizes the sense reading. The result is presented in figure 13. The raw final system presented non-linearities, specially when the level is close to the extremes, empty or full, that is compensated with proper calibration on the microprocessor.

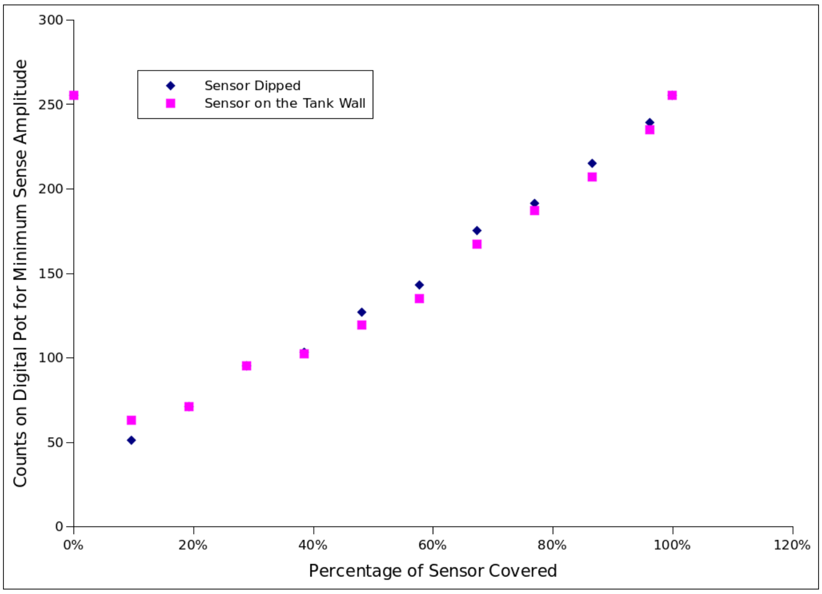

Figure 13. System Raw Response - Pot Counts per % of Sensor Covered

The resulting data was adjusted to calibration functions of many orders (table 1) using Gnumeric, with method NL-Solve, with a 100,000 iterations limit. The functions with higher order showed better R^2. The second order function, as a reasonable compromise between R^2 and computation requirements.

The chosen function is in 1.

$$
\begin{aligned}
Y =& a * X^2 + b * X + C \\
a =& -5,0822E - 06 \\
c =& 0,0060 \\
d =& -0,2085
\end{aligned}
\tag{1}
$$

Table 1. Calibration Function R^2 per Function Order

Label	Size
2	0,00299
3	0,00295
4	0,00292
5	0,00242
6	0,00218

After calibration, the full system response, measured at various fluid levels at the sensor, relative to its full size, is seen as in figure 14, and the deviation from the expected values are plotted in 15. The measurements were done both with the sensor exposed to the fluid on both sides, and on only one side, as identified in the figure.

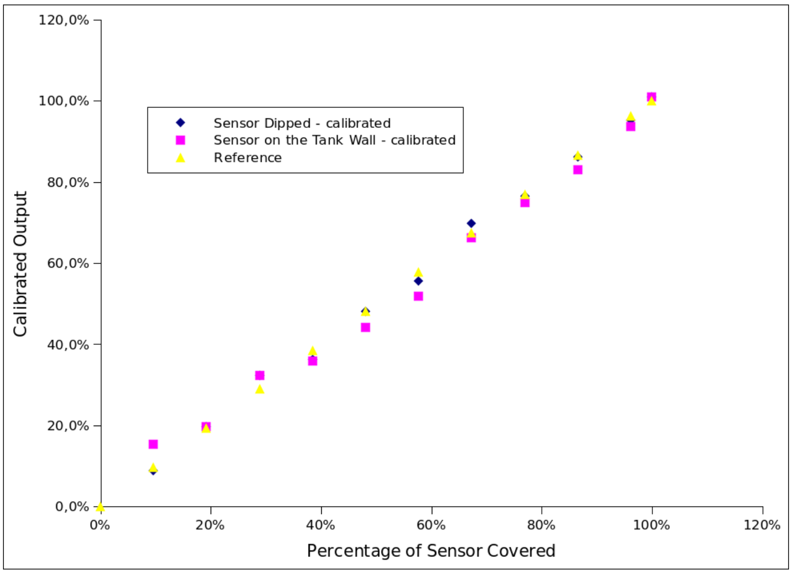

Figure 14. Full System Calibrated Response

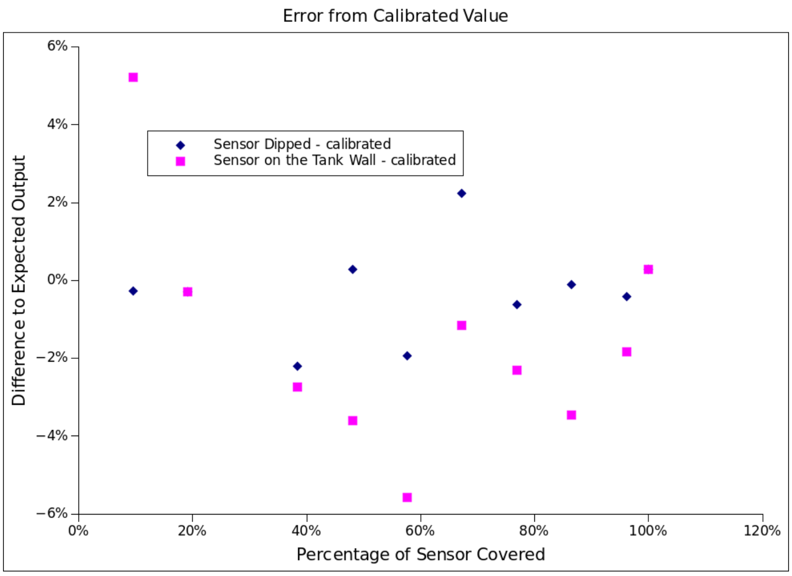

Figure 15. Full System Calibrated Observed Error

7. CONCLUSION

The system presented the expected result, with suitable linearity, sensibility and immunity to interferences.

The electrode is a thin film, that can be bonded to the fuelling nozzle, not obstructing the tank access, as was the original purpose of the development.

8. FUTURE WORK

Observing the system at work, it is clear that the control only works after major upsets, like a power up. When in regime, the system changes the wiper setting a few bits at at time, assuring the system is in the optimal wiper setting. From that, is clear that the cost of a sub-optimal optimization is limited to the time immediately after a upset, not influencing the performance while in regime. Being so, a simplified implementation using a sub-dollar microprocessor would offer adequate performance, and a very affordable set-up, that should be investigated.

9. REFERENCES

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10. RESPONSIBILITY NOTICE

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